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Research Article

Dunes under attack: untangling the effects of landscape changes on Iceplant invasion (*Carpobrotus* spp., Aizoaceae) in Mediterranean coasts

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Abstract

Invasive alien plants (IAPs) are a great challenge for biodiversity conservation and management. Temporal landscape analysis has a great potential for describing plant invasion process; however, conservation solutions accounting of landscape dynamics are still limited. This research aims to explore the spatial-temporal pattern of *Carpobrotus* spp. by analysing the IAP expansion and reduction processes in relation with landscape changes on Mediterranean coastal dunes. Based on detailed *Carpobrotus* spp. and local land-cover maps of the years 2011 (T0) and 2019–20 (T1), we described coastal dune landscape changes on invaded areas using transition matrices and identified areas of IAP expansion and reduction. We then calculated a set of class and landscape pattern metrics and explored the spatial configuration of invaded patches through trajectory analysis. We also analysed the relationship between *Carpobrotus* spp. patches and landscape pattern over time examining their respective temporal delta values, by Random Forest (RF) models followed by Partial Dependence analysis. The spatial-temporal characteristics of invaded patches and their contextual landscapes varied across coastal tracts experiencing IAP expansion or reduction. Trajectory analysis for IAP expansion areas evidenced an increased *Carpobrotus* spp. cover, accompanied by a rise in patch size, number and connectivity. According to RF models, these trends are related to a morphodynamical stable seashore and increased artificial surfaces. In contrast, trajectory analysis of IAP reduction area evidenced a decline in *Carpobrotus* spp. cover, with patches shrinking into smaller, more regularly-shaped forms. RF models suggest that this reduction is linked to coastal erosion, which compresses dunes against static infrastructures present in the foredune (e.g. roads, building etc.). Temporal landscape analysis provides a sound framework for understanding invasion dynamics across coastal mosaics shaped by the combined effects of factors, such as seashore dynamics and urban sprawl. This approach offers valuable insights for developing tailored management strategies that account for specific contextual nuances and enable informed planning of recovery actions.

Key words: Coastal dune vegetation, coastal erosion and accretion, Invasive Alien Plants, invasion process, landscape change, spatial pattern metrics

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Introduction

Biological invasions are a major biodiversity threat (Early et al. 2016; Stoett et al. 2019; Pyšek et al. 2020; Roy et al. 2023) and monitoring and managing them pose significant challenges (Early et al. 2016) partially addressed by global conventions (the Convention on Biological Diversity and the Kunming-Montreal Global Biodiversity Framework, COP 15) and regional legislation (e.g. Regulation EU no. 1143/2014 on Invasive Alien Species). According to the current knowledge and the legislation in force, preventing invasions, for instance of Invasive Alien Plants (IAPs hereafter), needs of rapid, efficient and replicable monitoring approaches to be implemented at different scales (Branquart et al. 2016). Within this framework, the monitoring of both invaded and non-invaded landscapes is crucial for the identification of areas in need of eradication and recovery activities as for early detection and for defining preventative measures (Branquart et al. 2016; Lozano et al. 2023, 2024).

Landscape analysis of invasion processes is important for understanding the spatiotemporal dynamics of each IAP and for defining adequate management strategies (Vaz et al. 2018; Liebhold et al. 2020). In this context, changes in invasion process, whether through expansion or reduction, are strongly influenced by land-use legacies (Malavasi et al. 2014; González-Moreno et al. 2017). For instance, knowing the temporal changes in the abundance and spatial arrangement of habitats more susceptible to biological invasion (Carranza et al. 2011), the land-use categories that facilitate or hinder the dispersal of IAPs propagules (e.g. artificial areas; Basnou et al. (2015); Rodewald and Arcese (2016)) and the elements that enhance or reduce connectivity between suitable areas for IAPs (Glen et al. 2013; Perry et al. 2016) is essential for gaining a deeper understanding of biological invasions across specific landscapes and regions over time (O'Reilly-Nugent et al. 2016). Furthermore, analysing the temporal dynamics of landscape changes is essential for understanding the complex relationships between invasion processes (whether in expansion or reduction) and native vegetation, as well as anthropogenic pressures. Such understanding is essential for developing effective conservation strategies and ecosystem management plans. Additionally, it may aid in identifying priority areas for intervention to prevent and manage IAPs (Branquart et al. 2016).

Amongst the most vulnerable landscapes to biological invasions, coastal dunes are of particular concern both globally (Chytrý et al. 2009) and in the Mediterranean Basin (Cao Pinna et al. 2021). Coastal dune landscapes can be found along approximately three-quarters of the world's shorelines. As complex, transitional and dynamic mosaics, they represent hotspots of highly specialised biodiversity (Martínez and Psuty 2008; Drius et al. 2016). In the Mediterranean Basin, coastal dune landscapes are deeply shaped and fragmented by natural processes amplified by human activities (e.g. coastal erosion, sea level rise; Bazzichetto et al. (2020)) and by human pressure (e.g. urbanisation, tourism etc.; Doody (2004, 2013); Malavasi et al. (2013)) both "squeezing" dune zonation to simplified small relict areas.

Amongst the worst IAPs impinging Mediterranean coastal landscapes, the *Carpobrotus* species (Aizoaceae) are of particular concern (Campoy et al. 2018). *Carpobrotus* spp. invasion on coastal dunes, alters plant diversity, negatively affecting the germination, survival, growth and reproduction of native species (Mugnai et

al. 2022) and transforms key soil physical and chemical properties including soil PH, salt content, moisture levels, nutrient content and microbial activity (Rodríguez-Caballero et al. 2020). *Carpobrotus* spp. invasion on coastal landscapes is shaped by the interplay of biotic factors (e.g. competition with native species, dispersal by native and introduced animals), abiotic features (e.g. coastal erosion and accumulation, seashore distance) and anthropogenic pressure (e.g. dune trampling, land take, artificial infrastructures; Bazzichetto et al. (2018a, b)). Consequently, factors such as seashore erosion and accretion (as discussed by Bazzichetto et al. (2020)) and different urban processes, such as expansion or stability (as outlined by Malavasi et al. (2018a)), may drive landscape dynamics and, in turn, influence invasion processes in contrasting ways. Given the extensive presence of *Carpobrotus* spp. on the Mediterranean coasts and their significant threat to biodiversity, considerable efforts have been directed towards intensive monitoring, detection and mapping (Underwood et al. 2003; Innangi et al. 2023), as well as for analysing their spatial pattern (e.g. Carranza et al. (2010); Malavasi et al. (2014)).

Monitoring and mapping of the *Carpobrotus* spp. distribution is crucial for developing and implementing targeted management and invasion control strategies (Lazzaro et al. 2020, 2023).

However, monitoring IAPs on dynamic dune mosaics by traditional approaches performed through field campaigns is both resource-intensive and costly. The field campaigns often cover limited areas due to accessibility constraints and historical distribution maps required for monitoring invasion dynamics at landscape scale are frequently unavailable (Müllerova et al. 2017; Cascone et al. 2021; Charbonneau et al. 2023). Consequently, the temporal changes of invasion process were barely explored and focused on limited number of IAP as *Acacia saligna* (Kutiel et al. 2004), *Carex arenaria* (Nielsen et al. 2011), *Oenothera drummondii* (Gallego-Fernández et al. 2019), *Carex kobomugi* (Charbonneau et al. 2020).

On the contrary, the increasing availability of remote sensing data is fundamentally transforming the monitoring of alien invasion processes on landscapes, offering the promise of advanced tools for tracking invasion dynamics across various spatial and temporal scales (Villalobos Perna et al. 2023). Such remote sensing tools may aid in dealing with new issues as the analysis of the intricate relationship between the temporal evolution of invasion patterns and the changes in landscape composition and configuration within complex environments such as coastal dunes.

In consideration of the above, the present research aims to analyse the spatial-temporal changes of *Carpobrotus* spp. invasion by analysing the invasion process of expansion and of reduction in relation to the landscape context pattern (i.e. composition and configuration) which occurred during one decade (2011 – 2019–20) in Mediterranean coastal dunes. Based on detailed bi-temporal land-cover maps and transition matrices analysis, we have described changes in the coastal dune mosaic and have addressed two main questions: (i) How does the *Carpobrotus spp.* invasion pattern vary within the coastal dune landscapes shaped by different factors (e.g. coastal erosion, urban expansion and ecosystems fragmentation)? (ii) How do the temporal changes of *Carpobrotus* spp. invasion pattern relate to changes in the composition and configuration of other cover classes within coastal dune landscapes?

We have hypothesised that the IAPs spread, establishment and growth are not uniform, but vary across landscapes shaped by different environmental variables (e.g. seashore dynamics, urban sprawl).

Materials and methods

Study area

The study area encompasses a representative coastal landscape of Mediterranean Holocene dunes on the Tyrrhenian coast in Central Italy (Lazio Region) of approximately 280 km (Fig. 1a; Mazzini et al. 1999; Amato et al. 2012). These dunes that are low and narrow and occupy a 400–500 m wide strip parallel to the shoreline (Acosta et al. 2003), in natural conditions, host a well-developed vegetation zonation, which follows a steep sea-inland abiotic gradient from pioneer communities dominated by annual plants to the inner sectors of Mediterranean scrub (Acosta et al. 2003; Fig. 1b). In addition to alien plant invasions (Bazzichetto et al. 2018a), the analysed dunes are highly threatened by coastal erosion (Bazzichetto et al. 2020), urban expansion (e.g. new buildings, recreational sites etc.), land take (e.g. agricultural expansion, afforestation, industrial and harbour development etc.) and ecosystems fragmentation (Malavasi et al. 2014, 2018a).

Carpobrotus acinaciformis (L.) L.Bolus and *C. edulis* (L.) N.E.Br. are mat-forming trailing succulent perennial herbs that are native to South Africa (Wisura and Glen 1993). Since both species tend to invade similar coastal dune habitats with comparable behaviour and impacts (Sarmati et al. 2019) and they commonly hybridise with each other, in their invasive range, they are frequently referred to as

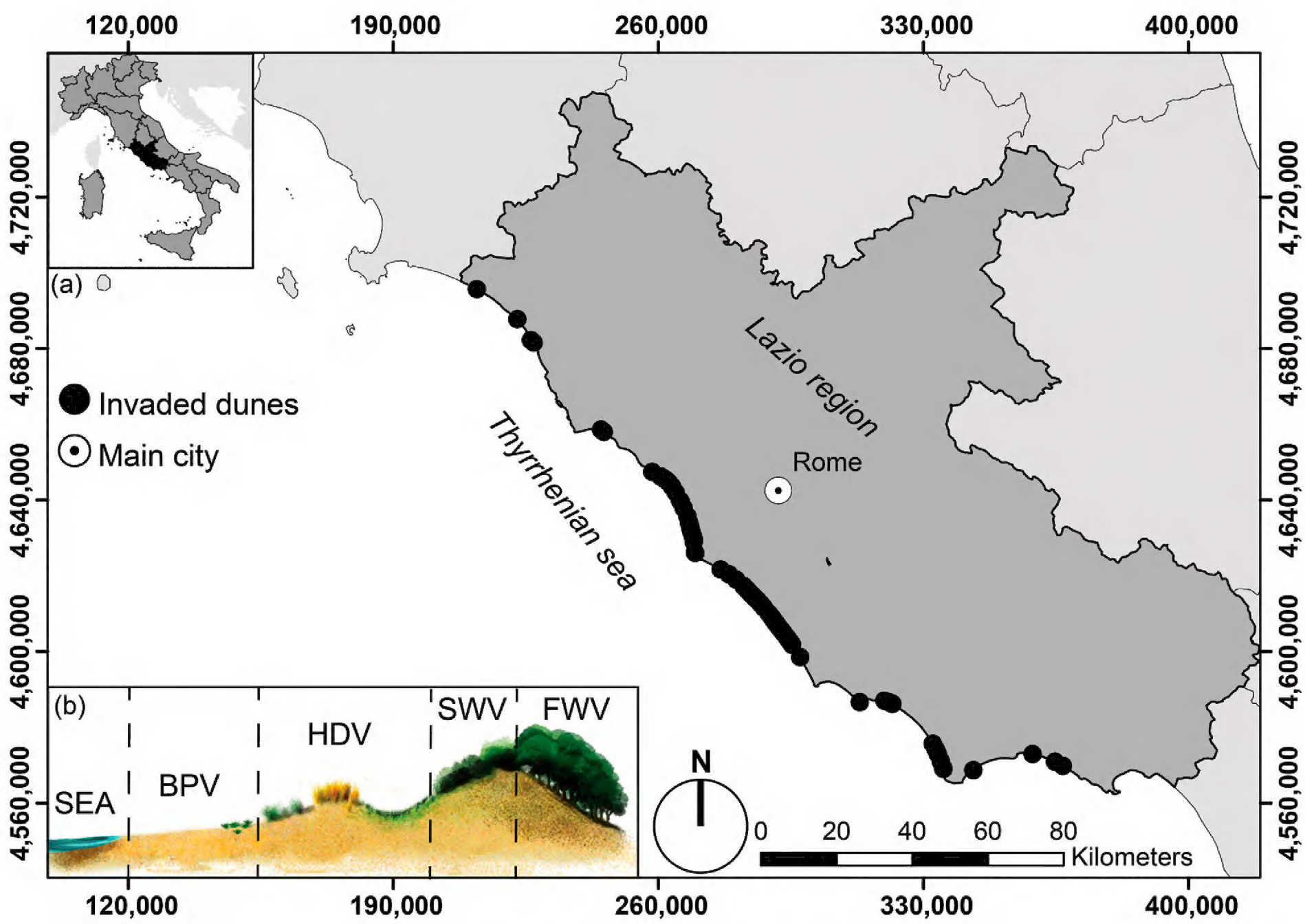

Figure 1. **a** Map of the study area (reference system WGS84 UTM 33 N, EPSG: 32633) showing the distribution of the invaded dune systems **b** schematic profile of coastal dune zonation with the acronym of the mapped natural coastal classes: SEA – sea water, BPV – beach with pioneer vegetation, HDV – herbaceous dune vegetation, SWV – Shrub woody vegetation, FWV – forest woody vegetation.

Carpobrotus spp. (Novoa et al. 2023). In the study area, *Carpobrotus acinaciformis* (L.) L.Bolus, *C. edulis* (L.) N.E.Br. and probably also hybrids between the two, were introduced as ornamental plants and for consolidating dunes (Campoy et al. 2018). As on other sectors of their invasive range, *Carpobrotus* spp. tend to invade herbaceous dune vegetation growing on shifting and fixed dunes preferentially and, to a lesser extent, clearings in shrubland and understoreys in woody vegetation and fore dunes (Carranza et al. 2011; Bazzichetto et al. 2018b).

Data collection and analysis

The workflow for analysing changes in invaded coastal landscapes and for assessing the interplay between invaded patch dynamics and contextual landscapes is illustrated in Fig. 2. It includes four key steps: (A) bi-temporal *Carpobrotus* spp. and land-cover mapping, (B) coastal dune landscape change, (C) spatial pattern analysis over time and (D) relationship between IAP dynamics and coastal landscape pattern.

Bi-temporal *Carpobrotus* spp. and land cover mapping

We selected two free web-mapping services providing spring/summer RGB orthophotos with a spatial resolution below 1 m to visually map *Carpobrotus* spp. patches greater than 1 m^2 across both past and present coastal dunes of Lazio Region (Fig. 2A) using a GIS environment (QGIS 3.22). Specifically, the imagery used (Suppl. material 1: table S1) included: spring and summer aerial RGB orthophotos from 2011 (T0 hereafter) available at the Italian National Geoportal (http://www.pcn.minambiente.it/mattm/servizio-wms/); and spring and summer satellite RGB orthophotos of the years 2019–20 (T1 hereafter) provided by Google Earth (Maxar Tecnhologies/Airbus, Inc.). To minimise the influence of seasonal changes on Mediterranean coastal landscapes (e.g. winter storms, tide etc.), we mapped *Carpobrotus* spp. patches during the same months (May-August) in T0 and in T1. Additionally, we addressed potential co-registration issues between the T0 and of T1 orthophotos by calculating the Root Mean Square Error (RMSE) of coordinate differences for 100 control points located in stable landscape features (e.g. buildings, road crossings, pools etc.; Coulter and Stow (2008)). This analysis revealed a georeferencing difference of 0.43 m, which is below the 0.50 m threshold considered indicative of very fine co-registered orthophotos (Talavera et al. 2022) and, thus, the alignment of the orthophotos used in this study was assumed as acceptable.

We mapped a total of 486 *Carpobrotus* spp. patches in T0 and 497 patches in T1. The *Carpobrotus* spp. patches were grouped into coastal tracts within non-overlapping circular buffer areas (Zuckerberg et al. 2020), each with a radius of 100 m (Fig. 2A). These buffer areas (hereafter tracts) were defined with the same centroid for both dates and include an extent widely used in coastal dune ecosystems where the relationship between landscape composition and biodiversity is evident (Bezzi et al. 2018; Malavasi et al. 2018a; Sperandii et al. 2019). Within each coastal tract containing *Carpobrotus* spp. patches, we generated a fine-scale (1:2000) land-cover/vegetation map (Fig. 2A) at the fourth level of detail of the CORINE land-cover legend (CL, Table 1, Acosta et al. (2005)). The semi-natural and natural cover types correspond to habitat types of European conservation concern (Annex I of the Habitats Directive 92/43/EEC; Table 1; Malavasi et al. (2013)). The accuracy assessment of the land-cover maps was based on 880 random control points (440

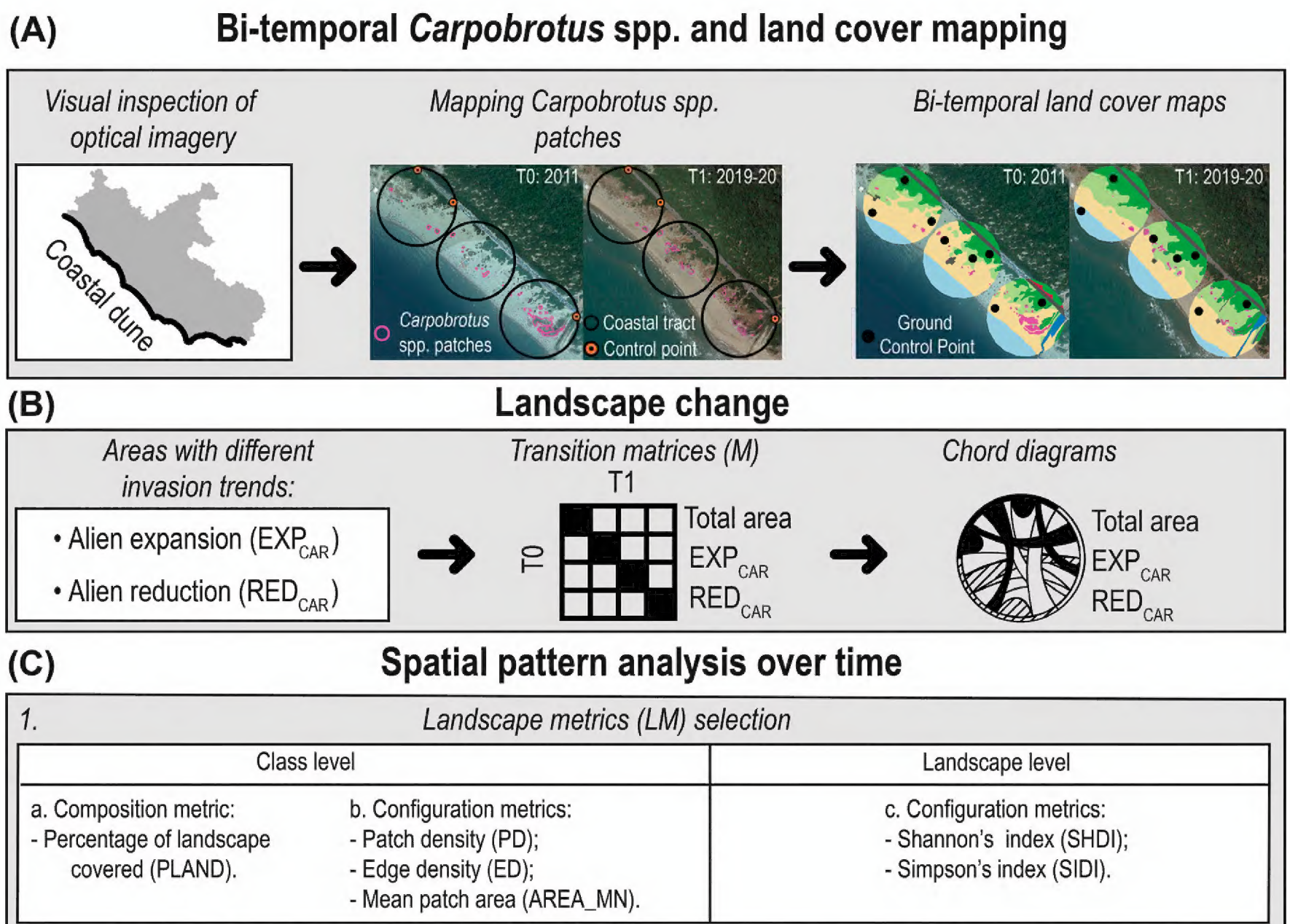

Figure 2. Schematic overview of the procedure implemented to analyse the spatiotemporal changes of *Carpobrotus* spp. invasion in relation with the landscape context. **A** Bi-temporal mapping of *Carpobrotus* spp. and land cover **B** analysis of landscape change **C** temporal spatial pattern analysis **D** assessment of the relationship between IAP dynamics and coastal landscape pattern.

points in T0, 440 points in T1). For the T0 map, the land-cover class for each control point was assigned using an existing detailed land-cover map (Carranza et al. 2008). For the T1 map, the classification of each point was determined by a dedicated field campaign carried out in Spring 2023. To evaluate the accuracy of the maps, confusion matrices were constructed and the following performance metrics were calculated: Overall Accuracy (OA%), Producer Accuracy (PA%), User Accu-

Table 1. Land-cover acronym, along with a detailed description (including Habitats of Conservation concern ex Dir. No. 92/43/EEC), CORINE land-cover category and the relative hierarchical code.

Acronym	Detailed description	CORINE category	CORINE code
ART	ARTificial areas including building, streets, urban fabrics, industrial surfaces.	Artificial areas	1.
BPV	Beach with Pioneer annual Vegetation. (EU 1210: annual vegetation of drift lines) and open sand without vegetation.	Open Sand	3.3.1.1.
HDV	Herbaceous Dune Vegetation growing on fore dunes. (EU 2110: embryonic shifting dunes, EU 2120: shifting dunes along the shoreline with *Ammophila arenaria*, EU 2210: *Crucianellion maritimae* fixed beach dunes, EU 2230: Malcolmietalia dune grasslands).	Partially vegetated dunes and densely vegetated dunes	3.3.1.2.
SDV	Shrub Dune Vegetation growing on fixed dunes. (EU 2250*: fixed coastal dunes with *Juniperus* spp., EU 2260: *Cisto-Lavenduletalia* dune sclerophyllous scrubs).	Mediterranean maquis	3.2.3.1.
FDV	Forests and woody Dune Vegetation. (EU 9340: *Quercus ilex* and *Quercus rotundifolia* forests, EU 2270*:wooded dunes with *Pinus pinea* and/or *Pinus pinaster*).	Forest	3.1.
SHV	Semi-natural Herbaceous Vegetation: abandoned meadows and pastures with different degrees of degradation or recolonisation.	Semi-natural herbaceous and ruderal vegetation	3.2.4.2.
WET	WETland non-forested areas of low-lying land flooded by fresh stagnant or circulating water.	Coastal Wetlands	4.2.
SEA	Tyrrhenian SEA.	Marine waters	5.2.
CAR	Invaded patches of *Carpobrotus acinaciformis, C. edulis* or their hybrids.	–	–

racy (UA%), Cohen's Kappa statistics (K), True Kill Statistic (TSS) and, given the possibility of unbalance data, we calculated also Balanced Accuracy (BA), a reliable metric to assess the performance of classification models on imbalanced datasets (Velez et al. 2007; Congalton and Green 2019).

Coastal dune landscape change

Based on the temporal dynamics of *Carpobrotus* spp. patches, we analysed overall invasion trends, ranging from nearly stable tracts to those exhibiting maximum expansion or reduction (from T0 to T1), capturing the full spectrum of landscape dynamics within the coastal dunes of the Lazio Region (Suppl. material 1: fig. S1). It is important to note that contrasting temporal trends, such as the expansion and reduction of *Carpobrotus* spp., may be driven by different environmental forces that influence landscape processes in distinct ways. Factors like seashore erosion and accretion (Bazzichetto et al. 2020) and varying levels of urban expansion or stability (Malavasi et al. 2018a) can shape landscape dynamics and, consequently, invasion processes, in opposing directions. To enhance our analysis, we categorised coastal tracts into two groups: a) *Carpobrotus* spp. expansion (hereafter EXP_{CAR}), including 60 tracts where the IAP cover increased and b) *Carpobrotus* spp. reduction (hereafter RED_{CAR}) gathering 35 tracts where the IAP cover decreased (Fig. 2B). By conducting separate analyses of EXP_{CAR} and RED_{CAR} tracts, we improved our understanding of the ecological connections between invasion dynamics and the broader landscape context in which invasive alien plants are embedded (Carranza et al. 2010; Malavasi et al. 2014; Bazzichetto et al. 2018b).

Landscape change for EXP_{CAR} and RED_{CAR} tracts was analysed by transition matrices comparing landscape cover classes in T0 and T1. The stability (transition matrix diagonal), the dynamism (other matrix elements) and the direction of change on EXP_{CAR} and RED_{CAR} coastal tracts were summarised by Chord diagrams (Fig. 2B; Gu et al. (2014)). As the outer ring of the chord diagram represents the extension of land-cover classes in T0, the internal arrows (e.g. size and

direction) indicate the transitions occurred towards other classes in T1. We used the R package "circlize" and the function chordDiagram to create the diagram (Gu et al. 2014).

Spatial pattern analysis over time

Changes in the spatial pattern of the coastal tracts invaded by *Carpobrotus* spp. were assessed by calculating and comparing, over time, a comprehensive set of landscape metrics (LM) that depict spatial composition and configuration at both the landscape level (LM_{land}) and the class level (LM_{class}) for the different time steps (T0 and T1; Fig. 2C; Table 2; Riitters et al. (1995)). We selected metrics able to depict distinct ecological processes within dune landscape patterns, whether these processes impede or facilitate plant invasion. These metrics may exhibit non-linear correlation issues and encompass key ecological processes and mechanisms essential for advancing the ecological understanding of *Carpobrotus* spp. pattern of change (Smith et al. 2009; Long et al. 2010). In particular, the selected metrics capture critical drivers of the invasion process on coastal dunes, including dune fragmentation and urban expansion (Malavasi et al. 2014, 2018a; Carranza et al. 2015), erosion/accretion dynamics (Bazzichetto et al. 2020), the loss of integrity within natural dune mosaics (Acosta et al. 2003) and the presence of both natural and artificial corridors facilitating alien propagule dispersal (Bazzichetto et al. 2018b).

For landscape metrics (LM_{land}), we calculated and compared over time two indices depicting landscape richness (number of land-cover classes) and evenness (relative abundance of each class). As Shannon index (SHDI), including a logarithmic transformation of abundance values (Table 2), is particularly sensitive to less abundant classes and constitutes a good indicator of equipartition, Simpson's index (SIDI; Table 2), is a reliable measure of dominance (McGarigal et al. 2012).

For class metrics (LM_{class}), we calculated and compared over time four indices, illustrating spatial composition (class abundance) and configuration (class spatial pattern, see Table 2; McGarigal et al. (2012)). Amongst these class metrics, PLAND, representing the percentage of the landscape covered by a given class, is a good surrogate for class dominance or rareness. PD, or patch density, describes the number of patches per unit area and measures class aggregation or dispersion in the landscape. ED, or edge density, calculated as the ratio between class perimeter and landscape area, measures class shape complexity or simplicity (e.g. edge effects vs. core areas) and provides an overview of the contact of a class with other land cover classes (e.g. high values may suggest the role as landscape matrix). AREA_MN, measured as the mean patch dimension of a given class, depicts the presence of large or small patches and is a good indicator of natural habitats fragmentation (e.g. smaller patches of native vegetation), as well as of invasive plants colonisation (e.g. increasing size of alien species patches over time; Table 2; McGarigal et al. (2012)). Metrics were calculated with FRAGSTAT 4.2 software (McGarigal et al. 2012).

Spatial pattern changes over time at class level ($LM_{classT0}$ vs. $LM_{classT1}$) were analysed by trajectory analysis (*sensu* Long et al. (2010)) depicting the relationship between composition and configuration metrics (Carranza et al. 2015; Malavasi et al. 2018b). For each class, a specific bi-temporal relationship space was produced by projecting in a Cartesian diagram the class configuration metric values (PD, ED, AREA_MN) computed for each coastal tract against the respective percentage of class cover (PLAND). Then, the arithmetic mean of each class metric

Table 2. Names (acronyms), formulas, descriptions, units of measurement and the associated spatial pattern levels (Class/Landscape) and facets (composition/configuration) of the selected pattern metrics. A = total landscape area, nj = number of patches of j-land-cover class, aij = area of the i-th patch of j-land-cover class, eij = total length of the i-th patch edge of j-land-cover class, m = total number of land-cover classes, Pj = proportion of the landscape occupied by j-land-cover class.

Name (Acronym)	Formula	Description	Unit / Range	Pattern facet
Class level (LM_{class})				
Percentage of Landscape (PLAND)	$\frac{\sum_{i=1}^{n_j} a_{ij}}{A} * 100$	Sum of the areas (m^2) of all patches of the *j*-land cover class, divided by coastal tract area (m^2) in percentage. Measure of dominance/rareness.	Percent (%) 0 ≤ PLAND < 100	Composition
Patch density (PD)	$\frac{n_j}{A}$	Density of patches of the *j*-land-cover class per unit area. Measure of aggregation/dispersion.	Number/ha PD > 0, no limit.	Configuration
Edge density (ED)	$\frac{\sum_{i=1}^{n_j} e_{ij}}{A}$	Edge length of *j*-land-cover class on the landscape area. Length of the contact with other classes. Measure of shape complexity/simplicity.	Metress/ha ED > 0, no limit	Configuration
Mean patch area (AREA_MN)	$\frac{\sum_{i=1}^{n_j} a_{ij}}{n_j}$	Area of *j*-land-cover class divided by its number of patches. Measure of fragmentation/colonisation.	Ha AREA_MN > 0, no limit	Configuration
Landscape level (LM_{land})				
Shannon Diversity Index (SHDI)	$-\sum_{i=1}^{m} (P_i * \ln P_i)$	Shannon's Diversity Index accounting for land-cover class richness and equitability. Sensitive to rare land-cover classes.	Natural number 0 ≤ SHDI < ∞ SHDI = 0 – no diversity	Composition
Simpson Diversity Index (SIDI)	$1 - \sum_{j=1}^{m} P_j^2$	Simpson's Diversity Index depicting land-cover class richness and dominance. Sensitive to dominant land-cover classes.	0 ≤ SIDI <1. SIDI = 0 – no diversity	Composition

(mean_LM_{class}) was plotted in the relationship space and the temporal trajectories for EXP_{CAR} and RED_{CAR} were drawn by connecting metric means chronologically with arrows. After a visual inspection of the relationship space to ascertain the means can be statistically compared, we assessed pattern landscape and class metric changes ($LM_{classT0}$ vs. $LM_{classT1}$ and LM_{landT0} vs. LM_{landT1}) by the non-parametric pairwise Wilcoxon rank test.

The temporal changes in composition given by the mean values of PLAND (e.g. in $PLAND_{CAR}$, $PLAND_{HDV}$, $PLAND_{ART}$ etc.) and configuration metrics assessed as the mean of PD, ED and AREA_MN (e.g. in PD_{CAR}, ED_{HDV}, $AREA_MN_{ART}$ etc.) were interpreted accounting of the specific non-linear relationship amongst them (Fig. 3; Long et al. (2010)). Given that numerous previous studies have demonstrated the non-linear correlation between landscape composition (PLAND) and configuration metrics (PD, ED, AREA_MN) across different environments, such as grasslands, forests, croplands and urban areas (Long et al. 2010; Su et al. 2012; Carranza et al. 2015; Malavasi et al. 2018b; Hermosilla et al. 2019; Zhang et al. 2020), it is essential to simultaneously analyse their temporal changes (Fig. 3). Such a concurrent interpretation of pattern metrics facilitates a nuanced understanding of the intricate dynamics interweaving these landscape facets (Long et al. 2010; Carranza et al. 2015).

In general, as described by Long et al. (2010), an increase in patch density (PD) accompanied by a decrease in PLAND values (e.g. numerous smaller patches) may indicate the fragmentation of natural habitats (Fig. 3a, Carranza et al. (2015)). Conversely, a simultaneous rise of PD and PLAND (e.g. numerous, larger patches) may reflect colonisation processes (Fig. 3a). Furthermore, a decrease in

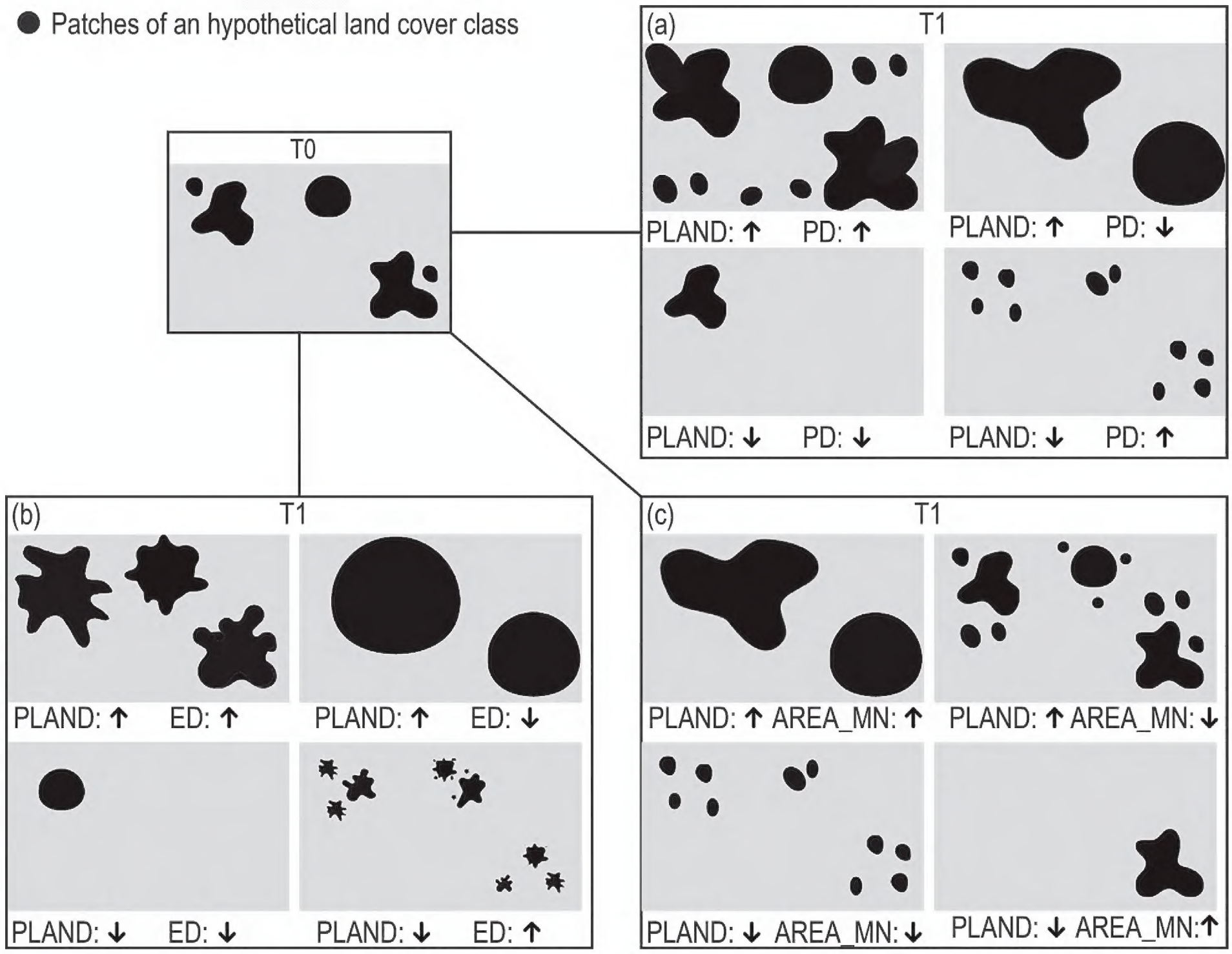

Figure 3. Combined effects of temporal changes (from T0 to T1) in composition (e.g. increasing or decreasing PLAND values) and configuration (e.g. increasing or decreasing PD, ED, AREA_MN values) of a hypothetical land-cover class: **a** changes in PLAND and PD **b** changes in PLAND and ED **c** changes in PLAND and AREA_MN.

PD could signify either increasing fragmentation (if accompanied by a reduction in PLAND) or habitat expansion due to the aggregation of several small patches into fewer, larger ones (if accompanied by PLAND increase; Yang and Mountrakis (2017)). Similarly, a rise in ED values can correspond to two scenarios (Fig. 3b). A simultaneous increase of ED and PLAND (e.g. larger and more irregularly-shaped patches) is likely associated with habitat frontal expansion. On the other hand, an increase in ED combined with a decline in PLAND (e.g. smaller irregularly-shaped patches) may indicate habitat fragmentation caused by patch shrinkage and irregular edge erosion (Carranza et al. 2015). On the other hand, decreased ED values can be associated with fragmentation if accompanied by a reduction in PLAND or with habitat expansion and the aggregation of irregular patches into larger, more regular ones if accompanied by an increase in PLAND (Yang and Mountrakis 2017). With regard to AREA_MN (Fig. 3c), a decline in average patch size combined with increasing PLAND may indicate habitat expansion with the formation of new small patches. Conversely, the simultaneous reduction of AREA_MN and PLAND (e.g. smaller patches) suggests fragmentation of larger patches into smaller ones, along with a reduction in the cover of the remaining patches (Long et al. 2010; Carranza et al. 2015). An increase in AREA_MN and PLAND (e.g. lager patches and higher dominance in the landscape) may indicate habitat expansion.

In contrast, an increase in AREA_MN accompanied by a reduction in PLAND reduction (e.g. large residual patches) may depict habitat loss, characterised by the disappearance of several medium-to-small patches and the persistence of one or few large patches (Malavasi et al. 2018b).

Relationship between coastal dune and IAP dynamics

To analyse the relationship between the spatial-temporal dynamics of invasion and the changes occurring on dune landscape, we computed the delta values of IAP pattern metrics (ΔLM_{CAR} = LM_{CAR} in T1 – LM_{CAR} in T0) and of coastal mosaic pattern ($\Delta LM = LM_{T1} - LM_{T0}$; Fig. 2D).

The visual inspection of bi-plots reporting changes on *Carpobrotus* spp. metrics (ΔLM_{CAR}) and landscape indexes (e.g. ΔLM_{class} and ΔLM_{land}) evidenced non-linear relations, so we explored invasion dynamics and landscape changes adopting a machine-learning approach organised in the following steps (Suppl. material 1: figs S2–S9). First, we computed the Variance Inflation Factor (VIF) on the delta of all the pattern variables and removed from further analysis those with high multicollinearity (VIF values ≥ 3), which can cause overfitting problems; then, we analysed the relationship of *Carpobrotus* spp. spatial-temporal pattern (ΔLM_{CAR}) with coastal dune landscape change (ΔLM_{class}, ΔLM_{land}) using Random Forest algorithm (RF; Breiman 2001) and we displayed the results using Partial Dependence Plot (PDP; Friedman 2001).

Specifically, we implemented a series of RF models (four for areas experiencing alien expansion: EXP_$\Delta PLAND_{CAR}$, EXP_ΔPD_{CAR}, EXP_ΔED_{CAR}, EXP_$\Delta AREA_MN_{CAR}$ and, four in areas undergoing alien reduction: RED_$\Delta PLAND_{CAR}$, RED_ΔPD_{CAR}, RED_ΔED_{CAR}, RED_$\Delta AREA_MN_{CAR}$). RF was implemented using the following settings: i) high number of uncorrelated decision trees (*Ntree* = 1000); ii) increasing number of variables randomly selected at each node of the decision tree (*Mtry* ranging from 2 to the total number of variables); iii) minimum number of observations in a terminal node (minimal node size, *MNS*: from 1 to 5; Probst et al. (2018)). Each RF model (using the R package 'caret', function train; Kuhn (2008)) was computed using a 10-fold cross-validation and we selected for further analysis the model with the highest coefficient of determination (R^2). The performance of the RF models was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE; Routh et al. (2018)). The relative importance of pattern metrics' change (ΔLM_{class} and ΔLM_{land}) in the RF models was determined using the Mean Decrease Importance (MDI) index (i.e. the Gini index with the sum of squares as an impurity measure). The marginal effects of landscape dynamics (ΔLMclass and ΔLMland) on *Carpobrotus* spp. spatial pattern changes (ΔLM_{CAR}) in the RF models (holding other variables constant, for example, median; Friedman (2001)) were descried by Partial Dependence Plots (PDP).

Results

Land-cover maps accuracy and transition matrix analysis

The produced land-cover maps are highly accurate (OA, K, TSS and BA greater than 85.682%, 0.833, 0.773 and 0.886, respectively; Suppl. material 1: tables S2, S3) and, thus, reliable for further landscape analysis. A comparison of land-cover

maps between T0 and T1, using transition analysis, revealed changes in the 18% of the landscape, with most land-cover classes shifting towards the neighbouring categories in a comparable manner (Fig. 4a–c; Suppl. material 1: table S4).

In both years, the dominant categories are Artificial areas (ART) and Open Sand (BPV) summing up to over the 40% of the mapped area, followed by herbaceous dune vegetation (HDV) and Sea (SEA) covering over 12% (Fig. 4a; Suppl. material 1: table S4). In EXP_{CAR} coastal tracts, the landscape was relatively stable with weak accretion processes (reduction of SEA class area; Fig. 4b), while in RED_{CAR}, landscape tracts have changed with a consistent increase in the SEA category at the expense of BPV (Fig. 4c; Suppl. material 1: tables S5, S6). Four cover classes (SDV, SHV, WER, FDV), which had limited extension in both time steps, were excluded from further analysis and modelling.

The chord diagram of the overall landscape evidences balanced shifts between CAR and HDV (Fig. 4a) differently, the separate analysis of chord diagrams revealing opposite landscape dynamics on EXP_{CAR} and RED_{CAR}. In EXP_{CAR} areas, we observed the expansion of CAR class at the expense of the HDV class (Fig. 4b), while in RED_{CAR} landscapes, we registered HDV replacing *Carpobrotus* spp. class; Fig. 4c).

Spatiotemporal trends of *Carpobrotus* spp.

The spatial pattern of *Carpobrotus* spp. patches changed significantly over time (from T0 to T1) presenting opposite trends in EXP_{CAR} and RED_{CAR} tracts (Fig. 5). In EXP_{CAR} tracts, *Carpobrotus* spp. patches increased in extent ranging from 0.41 m^2 to 865.84 m^2. Conversely in RED_{CAR} tracts, the extent of *Carpobrotus* spp. decreased ranging from – 1.65 m^2 to – 1322.25 m^2 (Suppl. material 1: fig. S10).

In tracts of IAP expansion (EXP_{CAR}), all *Carpobrotus* spp. spatial metrics significantly increased. The extension of invaded areas increased (greater $PLAND_{CAR}$, Fig. 5a–d) with *Carpobrotus* spp patches distributed on larger ($AREA_MN_{CAR}$, Fig. 5a, b), more numerous (PD_{CAR}, Fig. 5a, d) and irregularly-shaped patches (ED_{CAR}, Fig. 5a, d). On EXP_{CAR} landscape, we also registered a significant increase of artificial patch dimension ($AREA_MN_{ART}$; Suppl. material 1: fig. S11). On the other hand, in coastal tracts of IAP reduction (RED_{CAR}), the decline of *Carpobrotus* spp. ($PLAND_{CAR}$; Fig. 5a–d) coincides with simpler configuration metrics, indicated by lower values in $AREA_MN_{CAR}$ (Fig. 5a, b) and ED_{CAR} (Fig. 5a, c).

Spatiotemporal trends of *Carpobrotus* spp. in relation to landscape changes

Changes on *Carpobrotus* spp. pattern (ΔLM_{CAR}) are related with landscape changes (ΔLM_{land}), specifically concerning sea (SEA), herbaceous dune vegetation (HDV), the artificial surfaces (ART) classes (Figs 6, 7, Suppl. material 1: table S7). The Partial Dependence plots (Figs 6, 7) evidence that such relationship varies amongst areas of *Carpobrotus* spp. expansion (EXP_{CAR}) and reduction (RED_{CAR}). The RF models and their setup (*Mtry*, *Ntree*, *MNS*) provided an adequate description of the landscape dynamics of *Carpobrotus* spp. invasion, including changes in the spatial pattern of the surrounding landscape (ΔLM_{class} and ΔLM_{land}; Suppl. material 1: table S8). The spatial-temporal dynamics of *Carpobrotus* spp. patches ($\Delta PLAND_{CAR}$, ΔPD_{CAR}, ΔED_{CAR}, $\Delta AREA_MN_{CAR}$) are significantly correlated with coastal

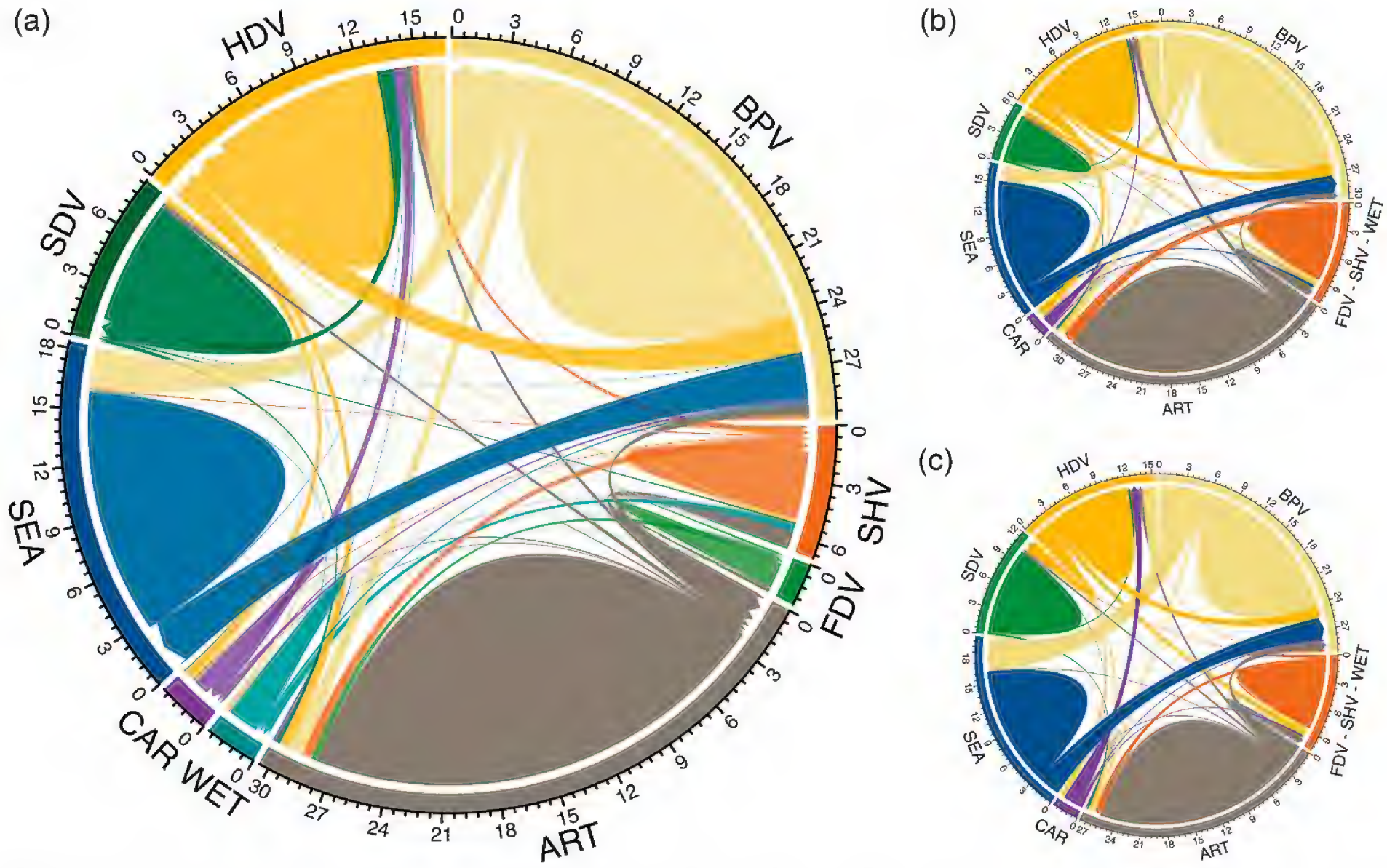

Figure 4. Chord diagrams for: **a** all coastal tracts **b** tracts with *Carpobrotus* spp. expansion (EXP_{CAR}) and **c** tracts with *Carpobrotus* spp. reduction (RED_{CAR}). The chord diagrams summarise the percentage (%) of each land-cover class in T0 (outer ring) that changed into another class to T1. The size and the direction of arrows represent transitions to other classes in T1. For example, an increase of HDV from BPV in T1 considering all coastal tracts. The proportion (%) of each land-cover class that remained stable over time is represented by the internal coloured circle. Land-cover classes: artificial areas (ART), beach with pioneer annual vegetation (BPV), herbaceous dune vegetation (HDV), shrub dune vegetation (SDV), Forest and woody dune vegetation (FDV), semi-natural herbaceous vegetation (SHV), wetland (WET), Tyrrhenian sea (SEA), *Carpobrotus* spp. (CAR).

dune landscape changes (with a minimum R^2 of 0.405 for the $EXP_\Delta PD_{CAR}$ model and 0.595 for the $RED_\Delta PLAND_{CAR}$ model; Figs 6, 7).

In coastal tracts of IAP expansion (EXP_{CAR}), the landscape change variables (RF_ΔLM) that better explain *Carpobrotus* spp. evolution ($EXP_\Delta LM_{CAR}$) are the size and the shape complexity of herbaceous dune vegetation, of the sea and of artificial areas ($\Delta AREA_MN_{HDV}$, $\Delta AREA_MN_{SEA}$, $\Delta AREA_MN_{ART}$, ΔED_{HDV}, ΔED_{SEA}, ΔED_{ART}; Fig. 6). A higher increment of *Carpobrotus* spp class cover ($\Delta PLAND_{CAR}$) occurs in correspondence with the reduction of sea-class surface ($\Delta AREA_MEAN_{SEA} \approx$ -0.25 to -0.50), with increasing contacts with artificial infrastructures ($\Delta ED_{ART} \approx$ 100 to 250) and with intermediate reduction in the number of natural dune vegetation patches ($\Delta PD_{HDV} \approx$ -150). We also registered an increase in the number of invaded patches (ΔPD_{CAR}, Fig. 6b) in correspondence with increasing edge length of beach-pioneering vegetation ($\Delta ED_{BPV} \approx$ 100 to 200) and of herbaceous vegetation cover ($\Delta ED_{HDV} \approx$ 100 to 200) and the reduction of herbaceous vegetation cover ($\Delta PLAND_{HDV} \approx$ less to -10). Concerning the increase of invaded patches edge length (ΔED_{CAR}, Fig. 6c), it tends to occur at increasing edge length of dune vegetation ($\Delta ED_{HDV} \approx$ 100 to 200) and of artificial areas ($\Delta ED_{ART} \approx$ greater than 200), as well as at decreasing cover of sea class ($\Delta AREA_MEAN_{SEA} \approx$ less to -0.25). As observed with invasion cover ($\Delta PLAND_{CAR}$), also the dimension

(a)

		EXP_{CAR}			RED_{CAR}		
		T0	T1	p-value	T0	T1	p-value
$PLAND_{CAR}$	mean	1.294	2.124	**	2.389	1.365	**
	U. CI	5.713	7.150		7.975	6.347	
	L. CI	0.000	0.141		0.078	0.000	
$AREA_MN_{CAR}$	mean	0.011	0.016	**	0.012	0.008	**
	U. CI	0.176	0.117		0.034	0.049	
	L. CI	0.000	0.000		0.002	0.000	
ED_{CAR}	mean	72.142	113.040	***	116.460	83.176	*
	U. CI	234.335	350.855		339.850	353.443	
	L. CI	0.000	20.067		7.768	0.000	
PD_{CAR}	mean	148.327	181.576	*	199.282	154.515	> 0.05
	U. CI	417.590	481.835		606.738	679.700	
	L. CI	0.000	32.294		32.367	0.000	

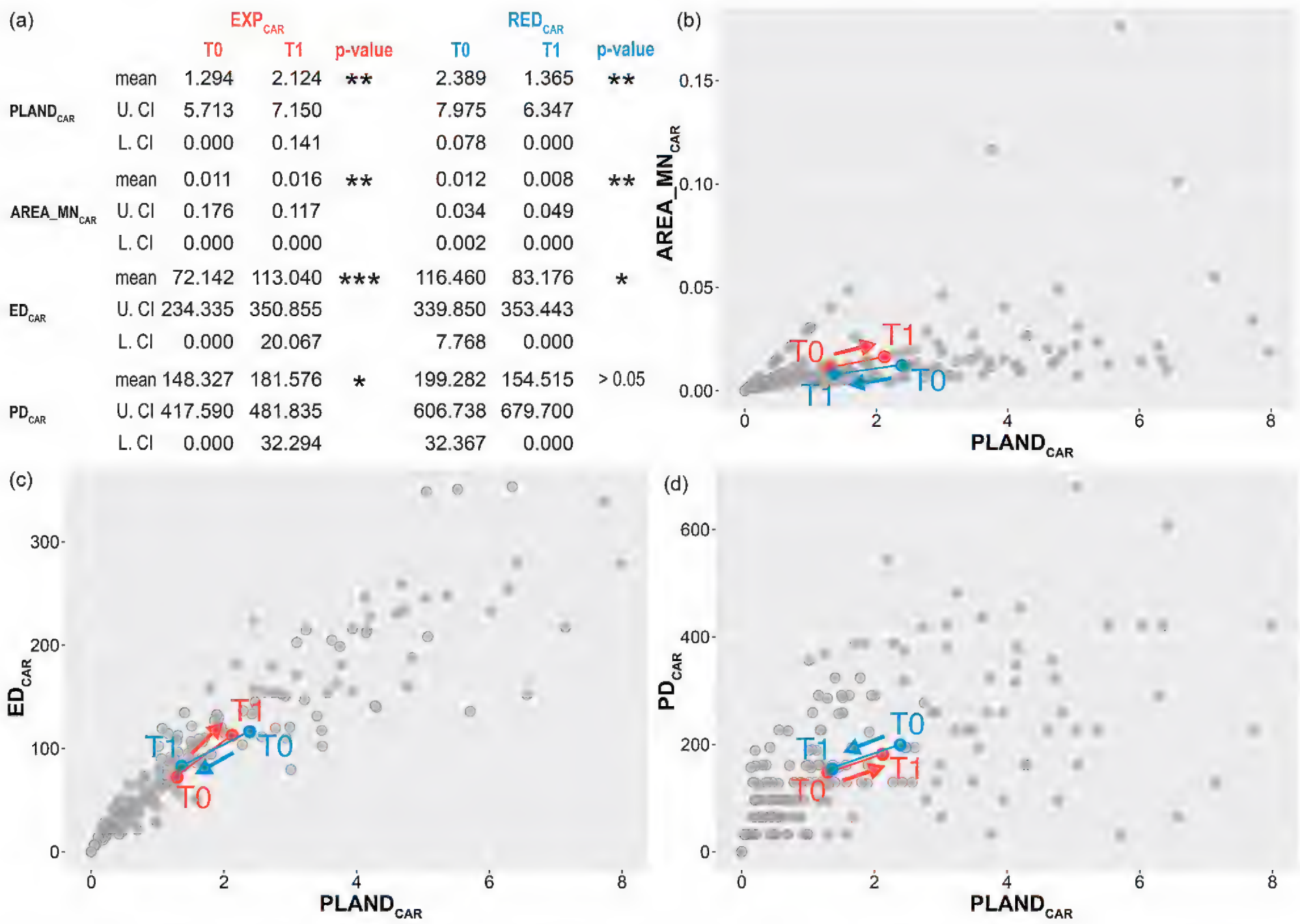

Figure 5. Comparison of *Carpobrotus* spp. pattern metrics ($PLAND_{CAR}$, PD_{CAR}, ED_{CAR}, $AREA_MN_{CAR}$) over time (from T0 to T1) in tracts of expansion (red: EXP_{CAR}) and reduction (blue: RED_{CAR}). **a** Kruskal-Wallis comparison of means and the respective confidence intervals (upper – U. CI, lower – L. CI; * = p-value < 0.05, ** = p-value < 0.01, *** = p-value < 0.001) **b–d** report the trajectory analysis of *Carpobrotus* spp. patches area ($AREA_MN_{CAR}$), edge density (ED_{CAR}) and patch density (PD_{CAR}) in relation to overall *Carpobrotus* spp. cover ($PLAND_{CAR}$). Grey dots represent the observed values of pattern metrics, coloured dots the arithmetic mean (mean of $PLAND_{CAR}$, PD_{CAR}, ED_{CAR}, $AREA_MN_{CAR}$) in each date (T0 and T1) in EXP_{CAR} and RED_{CAR} and arrows indicate the direction of temporal change.

of invaded patches ($\Delta AREA_MN_{CAR}$, Fig. 6d) tend to increase in correspondence with the reduction of sea-class surface ($\Delta AREA_MEAN_{SEA} \approx$ less to -0.25), with increasing or decreasing urban cover ($0.30 < \Delta AREA_MN_{ART} < -0.30$) and stable herbaceous vegetation edge length ($ED_{HDV} \approx 0$).

Partial dependence plots for less important change variables in EXP_{CAR} RF models are provided in Suppl. material 1: figs S12–S15.

In coastal tracts of IAP reduction (RED_{CAR}), the landscape change variables (RF_ΔLM) that explain *Carpobrotus* spp. contraction ($RED_\Delta LM_{CAR}$; Fig. 7) include both: class metrics of the main cover classes (e.g. ΔLM_{HDV}, ΔLM_{ART}, ΔLM_{SEA} and ΔLM_{BPV}) and landscape metrics (**Δ**SIDI). Stronger contraction of *Carpobrotus* spp class cover ($\Delta PLAND_{CAR}$; Fig. 7a) occurs in correspondence with changing beach pioneer vegetation edges length (decreasing $\Delta ED_{BPV} \approx$ -200 to -300 or increasing $\Delta ED_{BPV} \approx 100$), with increasing herbaceous vegetation cover ($\Delta PLAND_{HDV} \approx 10$), as well as with a consistent increase in artificial areas edges ($\Delta ED_{ART} \approx 100$ to 200). We also registered a decrease in the number of invaded patches (ΔPD_{CAR}, Fig. 7b) in correspondence with decreasing class metrics of herbaceous vegetation as edge length ($\Delta ED_{HDV} \approx$ -200) and number of patches ($\Delta PD_{HDV} \approx$

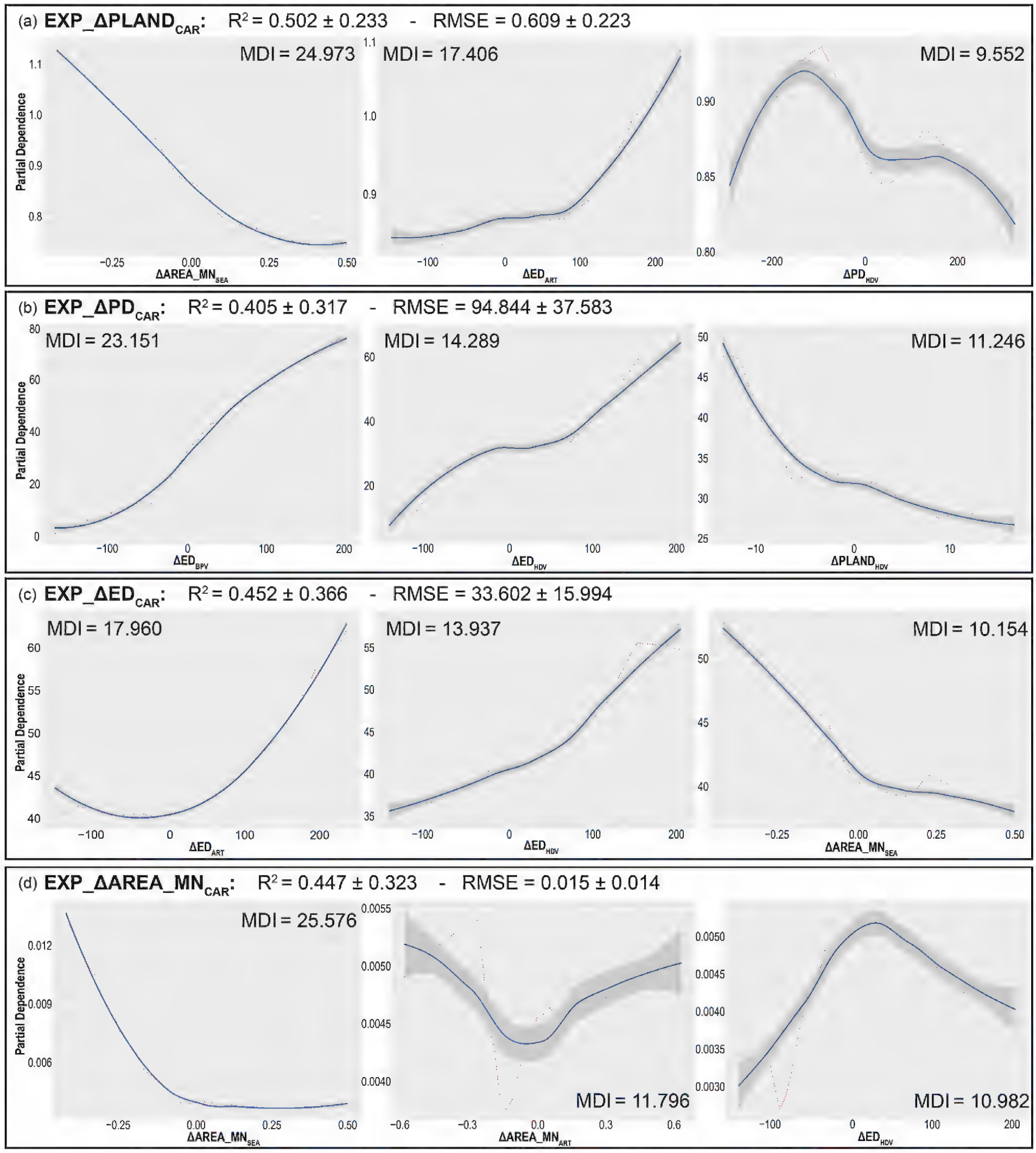

Figure 6. Partial dependence plots (PDP) using linear smoothing of the most important variables (over of 40% in cumulate importance) on the RF models for areas of alien expansion (EXP_ΔLM$_{CAR}$). **a** EXP_ΔPLAND$_{CAR}$ **b** EXP_ΔPD$_{CAR}$ **c** EXP_ΔED$_{CAR}$ **d** EXP_ΔAREA_MN$_{CAR}$. Red dotted lines represent raw PDP curves. The importance of each variable is indicated by the Mean Decrease Importance (MDI) value. For land-cover classes, see Table 1 and for pattern metrics description, see Table 2.

-100 to -200) and the increment of urban class cover (AREA_MN$_{ART}$ > 0). Regarding the decrease in invaded patch edge length (ΔED$_{CAR}$, Fig. 7c), it coincides with the reduction in herbaceous vegetation cover (ΔPLAND$_{HDV}$ ≈ -10) and edge density (ΔED$_{HDV}$ ≈ -200 to -250) and with the simplification of landscape diversity (ΔSIDI ≈ -0.025). A consistent reduction on *Carpobrotus* spp. class patch

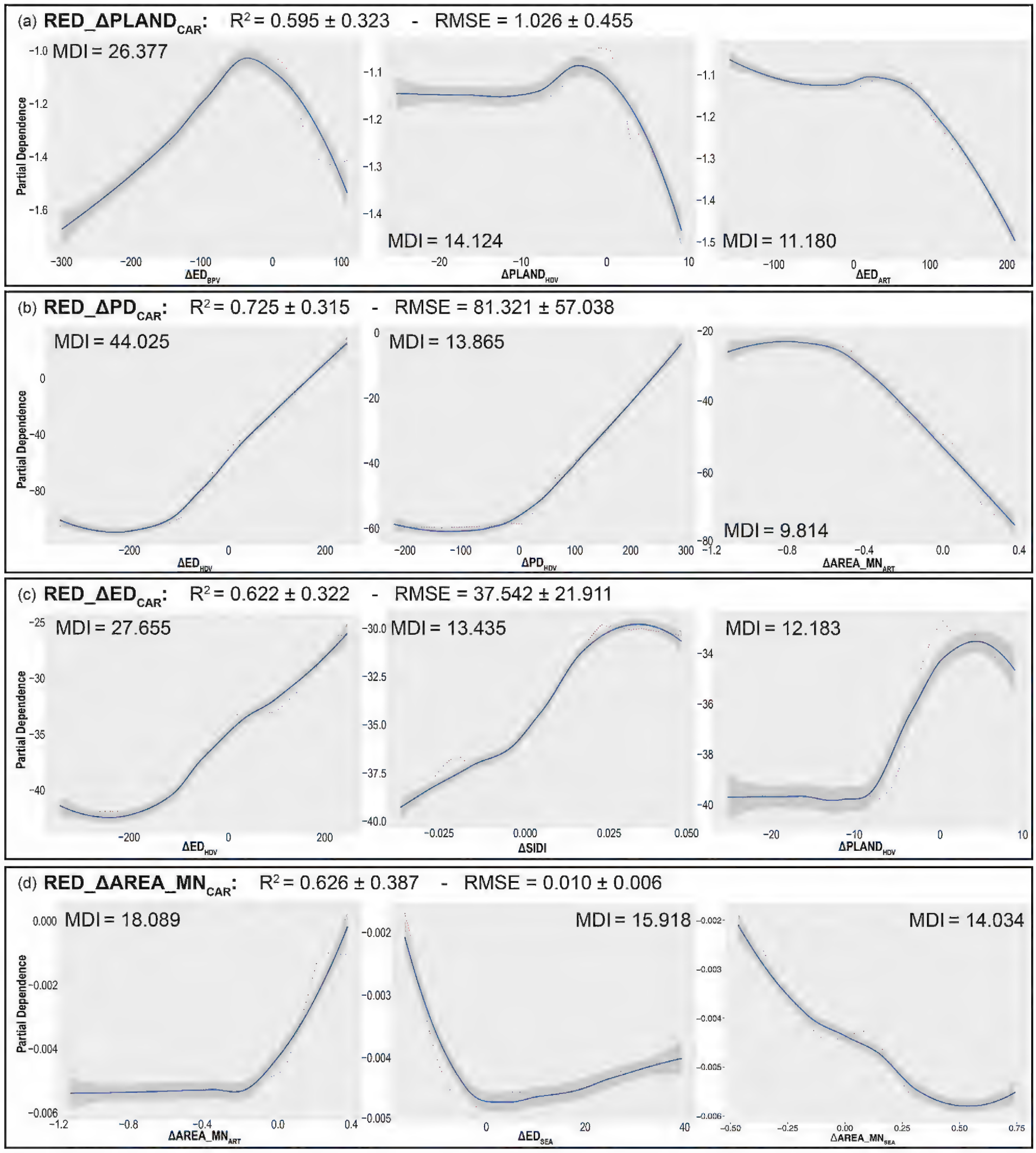

Figure 7. Partial dependence plots (PDP) using linear smoothing of the most important variables (over of 40% in cumulate importance) on the RF models for areas of alien reduction (RED_ΔLM$_{CAR}$). **a** RED_ΔPLAND$_{CAR}$ **b** RED_ΔPD$_{CAR}$ **c** RED_ΔED$_{CAR}$ **d** RED_ΔAREA_MN$_{CAR}$). Red dotted lines represent raw PDP curves. The importance of each variable is indicated by the Mean Decrease Importance (MDI) value. For land-cover classes, see Table 1 and for pattern metrics description, see Table 2.

size (ΔAREA_MN$_{CAR}$) seems related with increasing values of SEA class metrics as wider surface (ΔAREA_MN$_{SEA}$ > 0.25) and stable edges (ΔED$_{SEA}$ ≈ 0), as well as with the reduction of artificial surfaces (ΔAREA_MN$_{ART}$ < 0). The dependence trends of other change variables in RED$_{CAR}$ areas are reported in Suppl. material 1: figs S16–S19 for RED_ΔLM$_{CAR}$ models.

Discussion

We analysed the spatiotemporal changes in *Carpobrotus* spp. invasion and its relationship with landscape composition and configuration in tracts of expansion and reduction over time (from T0 to T1) in Mediterranean coastal dunes. Our results highlighted the importance of using satellite and aerial imagery with minimal co-registration errors to effectively analyse the temporal dynamics of coastal dune landscapes and invasion process (Talavera et al. 2022). Landscape changes have concerned approximately 20% of the total area with most changes involving significant shifts between neighbouring patches. Such shifts are quite common on highly dynamic ecosystems such as coastal dunes (Acosta et al. 2003; Drius et al. 2013). As on most of the Mediterranean seashores, urban areas and infrastructures (ART) resulted in being quite extensive (≈ 28%) and expanded over time at the expense of natural formations, such as beach and herbaceous dune vegetation (Malavasi et al. 2013).

Relationship between *Carpobrotus* spp. invasion and landscape dynamics in expansion tracts

Carpobrotus spp. tends to expand in coastal zones characterised by stable accreting seashore (where the SEA class area remains stable or diminishes) and by increasing urban surfaces (where ART class patches increase). The expansion of *Carpobrotus* spp. on coastal tracts experiencing seashore accretion and stability may be likely related with the fact that these seashore processes promote the development of herbaceous dune habitats (Bazzichetto et al. 2020) which are known to be especially susceptible for colonisation by invasive alien plants (IAPs) like *Carpobrotus* spp. (Carranza et al. 2011). Indeed, *Carpobrotus* spp. primarily expands by displacing herbaceous natural vegetation, confirming the high vulnerability of this natural habitat to IAP invasions. Our results gave new bi-temporal evidence of the habitat preference of *Carpobrotus* spp. to herbaceous habitats postulated in the past based on static data (e.g. Carranza et al. (2011); Bazzichetto et al. (2018a)) or using a diachronic analysis (Sperandii et al. 2018). The observed increase of IAP's and urban-patches cover, is likely attributable to the role of artificial areas as a source of non-native species (Carranza et al. 2010) and provides bi-temporal evidence in support of the propagule pressure theory.

The trajectory analysis evidenced a significant rise of all the considered *Carpobrotus* spp. spatial metrics denoting a consistent process of invasion. Indeed, the extension of invaded areas increased (greater $PLAND_{CAR}$) and *Carpobrotus* spp. tended to be distributed in more numerous (PD_{CAR}), larger ($AREA_MN_{CAR}$) and irregularly-shaped patches (ED_{CAR}). As observed in other colonisation processes such as forest regrowth (Malavasi et al. 2018b), the increase in the number of patches may denote the emergence of a new nucleus of colonisation, while the enlargement of patch area may indicate the growth of already established invaded points. On the other hand, the observed increase in edge length may indicate the maturity of invasion, with *Carpobrotus* spp. patches adopting the typical long-shaped pattern along the seashore of the invaded natural herbaceous dune vegetation (Carranza et al. 2010).

The pattern of expansion of *Carpobrotus* spp. (ΔLM_{CAR}) is significantly associated with landscape dynamics (ΔLM_{land}). Amongst the landscape change variables that best explain *Carpobrotus* spp. expansion, the seashore stability or accretion (ΔSEA close or higher than 0), the increasing surface and edges of urban areas (ΔART) and

the size and shape complexity of herbaceous dune vegetation, emerge as particularly influential factors. The observed increase in *Carpobrotus* spp. cover, patch size and edge length in stable or accreting coastal dunes (e.g. sea class surface reduction), highlights the strong correlation between the presence of dunes, their stability and the heightened susceptibility of landscapes to *Carpobrotus* spp. invasion. Our bi-temporal analysis-based results provide additional evidence supporting the vulnerability of dunes, a principle previously suggested by invasion risk models using the distance to the shoreline as a surrogate of coastal dune zonation (Bazzichetto et al. 2018a, b).

In tracts registering IAP expansion, *Carpobrotus* spp. patches become larger and more irregularly shaped in correspondence with an increase in the cover and edge length of artificial areas. This is likely linked to the role of built-up and urban structures, as well as artificial edges in driving invasion processes (Malavasi et al. 2014; Bazzichetto et al. 2018a, b). In these tracts, urban areas may play a double role: an important source of invasive alien propagules and key ecological corridors assuring landscape connectivity for the colonisation of new areas (Boscutti et al. 2022; Lozano et al. 2023). Our results also evidenced that altered coastal landscapes (e.g. detrimentally changed dune vegetation composition and configuration features) might undergo further modification due to the colonisation and spread *Carpobrotus* spp. (Malavasi et al. 2014). The creation of new artificial corridors (e.g. infrastructures) on fragmented coastal landscapes could aid the invasion process with detrimental effects on dune integrity and natural habitats. As observed for other IAPs, the registered landscape trends may be compatible with further growth of *Carpobrotus* spp. that conforming dense monospecific carpets could alter coastal dune landscape composition and configuration (Kozhoridze et al. 2022). The colonisation and expansion trends pinpoint the need for planning and implementing dedicated measures to contain and prevent further *Carpobrotus* spp. expansion at the expense of herbaceous dune vegetation classes which is urgent as it includes several habitats of European conservation concern (EU-2110: embryonic shifting dunes, EU-2120: shifting dunes along the shoreline with *Ammophila arenaria;* EU-2210: *Crucianellion maritimae* fixed-beach dunes, EU-2230: *Malcolmietalia* dune grasslands). These measures encompass both reducing and mitigating dune fragmentation and degradation processes, as well as monitoring activities in the most susceptible landscape elements to aid the implementation of effective prevention and early warning actions.

Relationship between *Carpobrotus* spp. invasion and landscape dynamics in reduction tracts

Within the coastal tracts of *Carpobrotus* spp. contraction (RED_{CAR}), landscape spatial-temporal characteristics resulted in being quite dynamic with an intense seashore erosion (SEA class area increase) that constrained the coastal dune zonation to small areas and that curtailed the spatial complexity of overall the natural mosaic (Doody 2004, 2013). In such areas, the SEA category is replaced by beach pioneer vegetation (BPV), that, in turn, substitutes herbaceous dune vegetation (HDV).

The decline in *Carpobrotus* spp. cover on coastal tracts experiencing seashore erosion may be attributed to the erosion's detrimental impact on habitats suitable for the invasive plant's colonisation, such as beach and herbaceous vegetation (Carranza et al. 2011; Bazzichetto et al. 2018a). While this hypothesis has primarily been examined in the context of management activities aimed at

eradicating *Carpobrotus* spp., further research is needed to validate its broader applicability (Chenot et al. 2018).

In these coastal tracts, *Carpobrotus* spp. tends to be substituted by herbaceous dune vegetation and its pattern in T1 resulted in being simplified into smaller and regularly-shaped patches with respect to IAP pattern on the T0. As evinced by trajectory analysis, the temporal reduction of invaded areas (lower $PLAND_{CAR}$) with *Carpobrotus* spp patches distributed on smaller ($AREA_MN_{CAR}$) and regularly-shaped patches (ED_{CAR}) suggest that *Carpobrotus* spp. is undergoing fragmentation. As observed in other fragmentation process (Wang et al. 2014; Carranza et al. 2015), the reduction of *Carpobrotus* spp. area into patches may denote the retreat and disappearance of invaded areas, while the reduction of patch size may indicate the contraction of the remnant invaded points.

The reduction pattern of *Carpobrotus* spp. (ΔLM_{CAR}) is linked to landscape changes (ΔLM_{land}), specifically those concerning coastal erosion (SEA) and land take (ART). Both processes contribute to the "squeezing" of dune zonation, compressing HDV and BPV communities into simplified small relict areas (Martínez et al. 2014; Gilby et al. 2021). In these tracts, the coastal "squeeze" process reduces suitable land space for coastal dune ecosystems and, consequently, the possibility to maintain their essential functions (Martínez et al. 2014). Under these "squeeze" conditions, only hard structures, such as building and human infrastructures, remain, while both *Carpobrotus* spp. patches and native vegetation tend to diminish and eventually disappear.

Within one decade, *Carpobrotus* spp. registered a decline on cover, patch size and edge length which occurred together with the simplification of natural and semi-natural land-cover classes (e.g. the reduction on cover, edge length and aggregation of herbaceous and pioneer dune vegetation) and overall landscape diversity (SIDI). Moreover, this reduction coincides with increased artificialisation (expanding urban areas in terms of area and edge length) and seashore erosion (expansion of sea area and edge length). The widespread decrease in landscape diversity and the deterioration of dune integrity (Acosta et al. 2003; Drius et al. 2013), combined with the fragmentation (*sensu* Wang et al. (2014)) observed in the invasion pattern of *Carpobrotus* spp., suggest a substantial influence of both abiotic factors (seashore erosion) and human-driven forces (urbanisation) on shaping the entirety of the coastal dune mosaic, encompassing both natural and invaded areas.

Conclusion

Our results highlight the significant potential of temporal analysis for monitoring invasive alien plants trends in complex dynamic mosaics like Mediterranean coastal systems. This temporal analysis of coastal composition and configuration has provided evidence of various processes: the stability of coastal dunes and the expansion of urban areas, that increase landscape vulnerability to invasions, as well as erosion and coastal "squeeze", which negatively impact invasion dynamics. These findings corroborate earlier conclusions from literature which were largely based on static data and emphasise the value of dynamic analyses for understanding and managing coastal landscapes.

The adopted temporal mapping and modelling approach effectively captures various changes in plant invasion, correlating them with ongoing landscape processes. This not only provides enhanced monitoring tools, but also advances our

understanding of invasion processes at a landscape scale, meeting the objectives outlined in the Convention on Biological Diversity and in the Regulation EU no. 1143/2014. Indeed, our results provide valuable insights for addressing management plans tailored to specific landscape contexts. For instance, in coastal tracts experiencing seashore accretion and urban growth, *Carpobrotus* spp. colonises stable coastal areas, displacing native herbaceous dune vegetation. In these tracts, urban expansion and the availability of open sand with herbaceous dune vegetation serve as key drivers of invasive alien plants (IAPs) proliferation. Consequently, targeted monitoring activities should be prioritised, focusing on herbaceous dune vegetation, to detect, control and eradicate *Carpobrotus* spp. patches. Conversely, the reduction of *Carpobrotus* spp. is observed in seashores affected by erosion and subjected to the "squeeze" process. This reduction leads to smaller, simplified patches, indicating fragmentation and the eventual disappearance of invaded areas. Therefore, management actions and projects aimed at mitigating the coastal erosion and the "squeeze" process (Leo et al. 2019) and preventing the potential re-invasion of *Carpobrotus* spp. should be implemented in reduction tracts.

The proposed methodology could be further extended to other datasets to calculate invasion trends through a fully temporal assessment. Additionally, new multi-temporal analysis may be adopted to evaluate the effectiveness of IAP management actions over time and support the implementation of adaptive management strategies. The use of temporal maps and data offers a cost-effective solution for monitoring IAPs across broad geographic areas, addressing the resource constraints often associated with field data collection campaigns. Therefore, we strongly advocate for the adoption of temporal landscape analysis as a monitoring tool to bridge the gap between scientific knowledge and IAP management practices. This approach provides tailored and efficient solutions for environmental managers, facilitating more informed and effective decision-making.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary data

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Data type: docx

Explanation note: Results of non-linear relations between invasion dynamics and landscape changes (**figs S1–S8**). Confusion matrices of land cover maps in 2022 (**table S1**) and in 2012 (**table S2**). Transition matrices of land cover changes in all study area (**table S3**), in areas with expansion of *Carpobrotus* spp. invasion (**table S4**), and in areas with reduction of *Carpobrotus* spp. invasion (**table S5**). Trajectory analisis of Artificial class pattern metrics (**fig. S9**). Result of Variance Inflation Factor (VIF, **table S6**). Results, performances, and variable importances of Random Forest models (**table S7**). Partial dependence plots (PDP) of random forest models using linear smoothing from the 4th to the 13th variables in order of importance (**figs S10–S17**).

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